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COMPUTERIZED FIVE-CHANNEL SYSTEM FOR REAL-TIME MONITORING OF FLOAT-GLASS RIBBON IN THE HOT ZONE OF THE ANNEALING FURNACE

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The automated five-channel system produced by the TEOS Company for controlling the float-glass ribbon thickness in real tine in the hot zone of the annealing furnace is based on tandem low-coherence interferometry. Continuous monitoring of glass ribbon thickness offers fundamentally new opportunities to engineers and operators for controlling the process. The operating principle, advantages of the system, and the result of its performance at glass factories are described.

In view of increasing requirements on product quality, various technological parameters need continuous precise monitoring. In particular, thickness is one of the key parameters in the glass industry. The majority of polished glass is currently produced by the most cost-efficient float method. Clearly, to improve the product quality and to minimize glass melt losses, the glass ribbon thickness has to be constantly monitored either in the ribbon-formation zone, or immediately after this zone.

Until recently the only method for monitoring ribbon thickness in Russia and the CIS countries was manual checking at the cold end of the line. The deficiencies of this method are obvious. First, the time lag between an operator's actions and a measurement is 30 – 60 min (allowing for the measurement time). Second, the measurements are not continuous: they occur at best 1 – 2 times per hour. Some western factories have installed triangulation systems for thickness monitoring. However, they have a number of serious drawbacks, are expensive, and difficult to service.

In 2000 – 2002 researchers at the Institute of Microstructure Physics of the Russian Academy of Sciences developed the first prototypes of an automated system for monitoring glass ribbon thickness based on the principles of tandem low-coherence interferometry [1]. The prototypes were tested in industrial conditions at the Borskii Glass Works and continue to function adequately. However, it has become evident that theses prototype have to be substantially upgraded to serve as industrial instruments. At the end of 2004 and in early 2005 instruments of a new generation with significantly improved reliability and precision parameters were installed at the glass factories in Tokmok (Kirguizia) and Gomel (Belarus).

The TEOS Company, which focuses on developing automated control systems, was founded by researchers of the optical instrument group from the Institute of Microstructure Physics of the Russian Academy of Science. By now the control system has been completely reconstructed. The up-to-date version satisfies the European standard requirements and some new options have been added compared with the earlier versions [2].

Optofiber low-coherence tandem interferometry as a method for remote measurement of thickness. Let us first briefly consider the principle of the system operation, as it usually generates numerous questions from consumers. We do not intend to describe every nuance of the method used but will focus on the main physical principles of the system, since this makes it possible to better understand the advantages of the system, its precision characteristics, and ample opportunities for applying this system in various fields of science and engineering.

The measurement method used in our system is called tandem low-coherence interferometry. The main feature of this method is using a wide-band light source with a small coherence length (in our case it is a superluminescent diode with spectral width around 40 nm and a coherence length of approximately 20 μm).

Let us consider the concept of the "coherence length" and its correlation with the source spectral width. The coherence length for a strictly monochromatic source is equal to infinity. This means that when a beam generated by such source is directed to a certain interferometer (for instance, Michaelson interferometer), exit interference bands will be

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observed under any difference of the interferometer branches. Using a source with a finite spectral width makes the situation different. In this case interference can be observed only provided that the difference in the optical paths of the interfering waves is less than the coherence length, which can be estimated as

$$L_{\text{coh}} = \lambda^2/\Delta\lambda,$$

where λ is the central wavelength of the source $\Delta\lambda$ is the spectrum width.

The interference of quasimonochromatic light is discussed in more detail in [3, 4]

It is more interesting when the light from a wide-band source consecutively passes via two interferometers. Such pair is often called a tandem of interferometers. In this case interference is observed when the differences of the branch lengths of two interferometers differ from each other by a value smaller than the source coherence length, i.e., the following condition is satisfied:

$$|L_2 - L_1| < L_{\text{coh}},$$

where L_1 and L_2 are the differences of the branch lengths of the first and the second interferometers.

In this case the interference of two waves is observed: the first wave passes via the short branch of the first interferometer and the long branch in the second one; the second wave passes through the long branch of the first interferometer and the short branch of the second one. In our case the glass ribbon itself acts as the first interferometer (Fabry – Perot low-robustness interferometer) illuminated from a distance of 1.5 m, whereas the second measuring interferometer has the possibility of controlled variation of the branch lengths difference. The interferometers are connected via an optic fiber, which makes it possible to install the precision measuring interferometer in favorable conditions, far from the measurement site.

For objectivity, let us briefly consider another method for measuring glass ribbon thickness, namely, the triangulation method [5] using the reflection of a slanted light beam from the nearest and furthest surfaces of the ribbon, where the sample thickness is determined based on measuring the distance between the reflected beams. Despite the simplicity of this scheme, it has a number of significant drawbacks. The beams reflected from different surfaces then propagate via different paths. Consequently, the presence of turbulence (which is inevitable in a furnace at high temperatures) produces an uncontrollable error, which grows as the receiver gets further apart from the ribbon. Furthermore, the trembling of the ribbon and the presence of a wedge (nonparallel planes) across the ribbon thickness also produces an error that grows as it gets further from the sample.

Thus, for precise measurement one has to ensure a small distance between the receiver and the glass ribbon. Since the temperature in the measuring zone is high (over 500°C), the existent triangulation systems for measurements in the hot zone are equipped with a powerful water-cooling system and a system of forced air cooling of optical heads to protect them from the annealing furnace atmosphere. The need to maintain a constant distance to the ribbon requires a rather complicated system for positioning the optical heads. Furthermore, the close distance of the head to the ribbon involves a risk of the optical head breaking in the case of an emergency on the float line, such as intense warping or break of the ribbon. All this increases the cost of the system and its maintenance, and the system sensitivity to the ribbon wedge produces a perceptible error during the transition from one glass thickness to another.

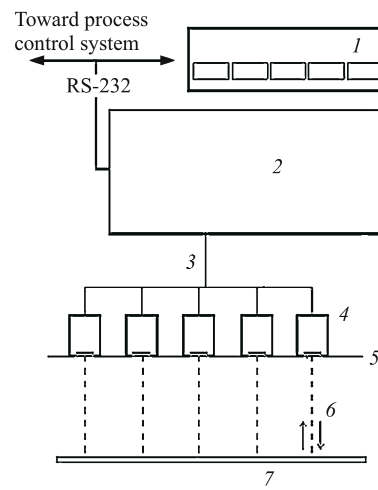

Fig. 1. General scheme of 5-channel control system: *1*) indicator; *2*) optoelectron measuring-control instrument; *3*) optofiber cable; *4*) optical heads; *5*) annealing furnace roof; *6*) probing beam; *7*) glass ribbon.

Let us analyze the industrial system for measuring glass thickness produced by us that is based on tandem low-coherence interferometry.

Automated 5-channel system for technological control of float-glass ribbon thickness in real time in the hot zone of the annealing furnace. A diagram of this system is shown in Fig. 1. The tandem of interferometers described above is implemented as follows. Light from a superluminescent diode is directed to the input of the precision interferometer positioned inside an optoelectron block. The interferometer has the option of a precision controlled variation of the branch lengths difference. Upon exiting from the interferometer, the light arrives at the optofiber beam splitter and becomes split among the measuring channels. From the splitter the light arrives at each channel independently via its own cable to an optical head that constitutes a system of projecting the radiation from optical fiber to the ribbon and collecting the light reflected from the ribbon back to the fiber. Next the light goes to the photoreceivers that are individual for each channel. Upon scanning the difference in branch lengths of the measuring interferometer, a signal is generated at the exit of each photoreceiver corresponding to the optical thickness of

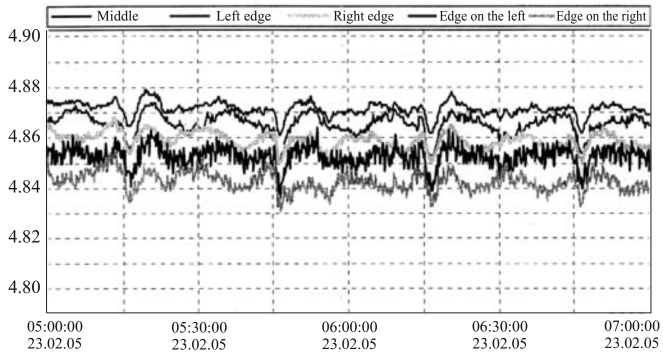

Fig. 2. Behavior of glass ribbon in time. The thickness "drops" in all five channels correspond to a flame reversal in the melt tank.

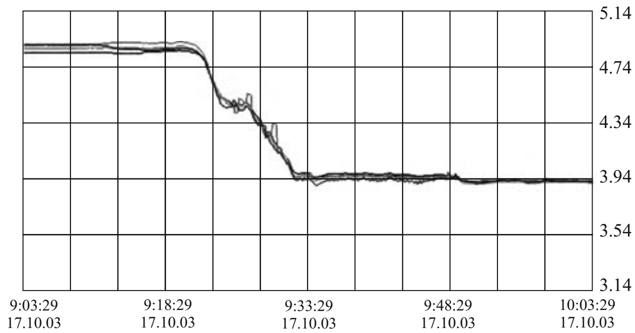

Fig. 3. Plot of transition from one glass thickness to another on the float line.

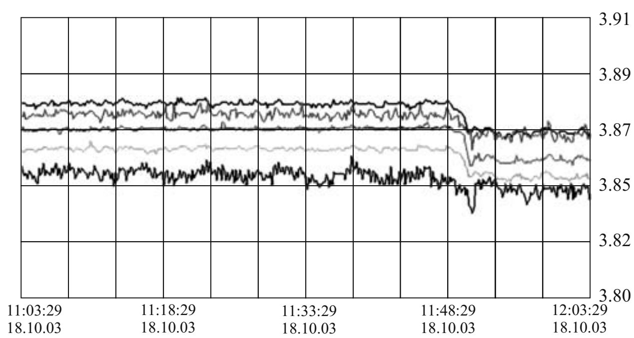

Fig. 4. Decreasing nonuniformity of glass ribbon thickness.

the glass ribbon (i.e., the product of its geometric thickness by the refractive index) in the particular channel. As a result, we obtain data of simultaneous independent measurements of glass thickness in several channels. The measurement precision is the same in all channels and depends on the measuring interferometer. In principle, the number of channels can be arbitrary; however, experience has shown that it is optimal to have five channels uniformly distributed over the ribbon width.

The obvious advantage of this method is the simplicity of the optical head design, which does not include moving or electron components. Consequently, these optical heads and the whole system does not require special cooling or maintenance. Furthermore, the probing of the ribbon can be implemented from a relatively remote distance (up to 1.0 – 1.5 m from the glass ribbon); therefore, the system does not require special protection in the case of an emergency occurring on the float line. The most convenient and advisable place for fixing the optical heads is the roof of the annealing furnace, as close as possible to the float tank, which substantially facilitates prompt control of the process.

Let us consider some results of the operation of this system at several factories (by February 2006 six systems have been installed at the following works: Borskii Glass Works, Russia; Gomel'steklo JSC, Belarus; Interglass JSC, Kirguizia; Saratovstroisteklo JSC, Russia).

Note that for the maximum effective use of this system, operators and technologists at the float line should (in addition to current monitoring) have access to data on the glass ribbon thickness in the preceding period. In the earlier versions of the system, the measurement database and its visualization were the responsibility of the system user. At present we have developed additional software that is offered as an option for this system.

Figure 2 shows the behavior of a glass ribbon in producing glass of the same thickness. It can be seen that the glass thickness actually has an undulating structure. In fact practical experience shows than any operation on a float line has a response in thickness. For instance, Fig. 2 shows periodic "drops" in the glass ribbon thickness. The analysis of the correlation between the system readings and the operations performed on the float line indicated that these peaks are caused by the reversal of the flame in the melt tank from one side to another.

Since the measurement method forming the basis of the system is not sensitive to the wedge effect (nonparallel surfaces) and trembling of the glass ribbon, the system enables us to monitor thickness even during the transition from one glass thickness to another. Such control makes it possible to substantially shorten the transition duration. Figure 3 shows the plot of a transition from one glass thickness to another at the Borskii Glass Works, two years since the installation of the system. It can be seen that the transition lasts 5 – 7 min. Such brief transition time allows for flexible production control and makes it possible to produce a glass product range most in demand at the moment.

Another important information that can be obtained from the system is a nonuniformity in glass thickness across the ribbon width. Figure 4 shows a very interesting moment when the operator decreases thickness nonuniformity by using the edge-forming machines. Considering the growing requirements on uniform thickness in automobile glass or glass used for multiple window panes, the continuous monitoring of thickness provides an additional competitive edge by improving the quality of the product.

Calibration and metrological certification of the system. The parameter measured by the system is the optical thickness of the glass ribbon. It is defined as

$$D = nd,$$

where D is the optical thickness of the glass ribbon; n is the effective refractive index; d is the geometric glass ribbon thickness.

Furthermore, it is necessary to take into account the thermal expansion of the ribbon in the measurement zone.

Thus, for determining the geometric thickness of a glass ribbon after cooling, the measured optical thickness should be divided by the effective refractive index, which depends on different parameters, such as temperature in the measurement zone or the batch composition. However, the accumulated data show that in the case of a steady production process the dispersion of data caused by temperature instability or the batch composition is not more than 5 μm. Therefore, the system does not require constant checking; it is sufficient to perform the calibrating procedure just once during the start-up period.

The operating experience shows that it is desirable to have an additional measuring channel located not inside the annealing furnace but next to the optoelectron block of the system. The advantages of such optical head is that the user can check the performance of the system by placing calibrated glass samples under this head. Obviously, calibrated glass cannot be placed beneath the optical head in the hot zone. Furthermore, an optical head can be installed as well in the quality control department, and it can be metrologically certified and subsequently used as a measuring instrument for product control. If this head is connected with the measurement channels in the hot zone, an automatic calibration of the system can be provided. Such upgrade of the system seems very promising and significantly expands the functionality of the system.

The main purpose of the system is monitoring glass ribbon thickness. It can be seen from the plots shown here that continuous thickness monitoring allows for shortening the time of transition from one thickness to another to 5 – 10 min. An operator having such control system can maintain the glass ribbon thickness near its minimal admissible limit, which helps to save glass melt. Furthermore, it becomes possible to significantly decrease thickness nonuniformity across the glass ribbon width. Considering that the construction and automotive industries impose ever stricter requirements on glass quality, this effect is important.

The advantages of the system include its simplicity and low maintenance cost. The system does not required additional cooling and consumes not more than 300 W of electric power, which is comparable to a modern PC. Moreover, an appropriate placement of optical heads on the annealing furnace roof makes it possible to completely protect the system from such emergencies as a ribbon break off.

Six systems of this type have been installed at glass factories of Russia and the CIS countries. The six-year service has proved their high reliability and stability. The users of the system estimate its payback period as about 6 months.

Another promising application for new measuring systems is measuring sizes of glass articles of complex shapes, such as wall and bottom thickness in glass bottles or thickness of fine glass tubes.

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